Crusts of Strange Quark Stars and Pairing in Quark Matter

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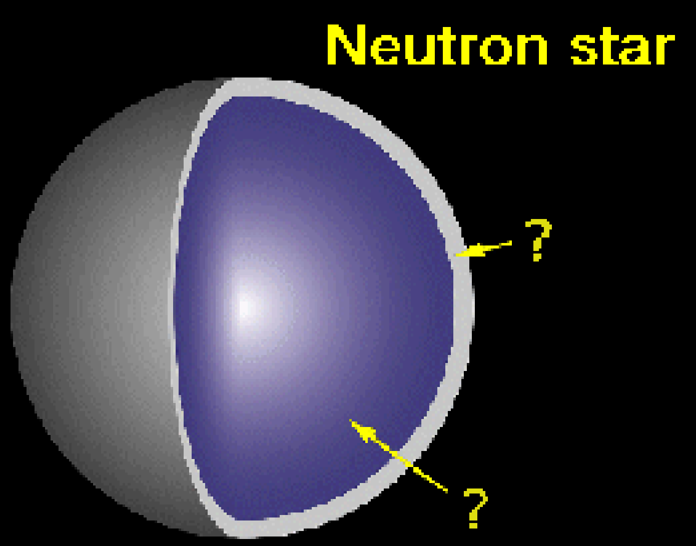
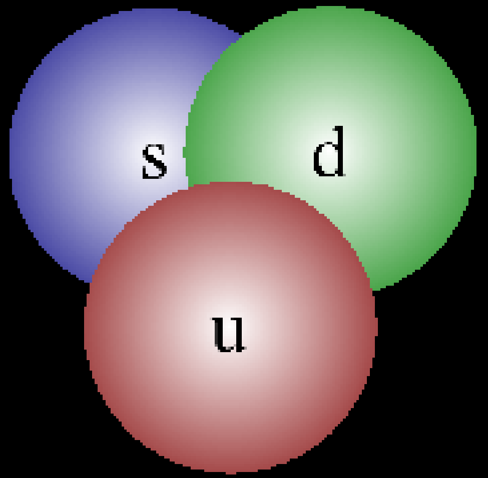


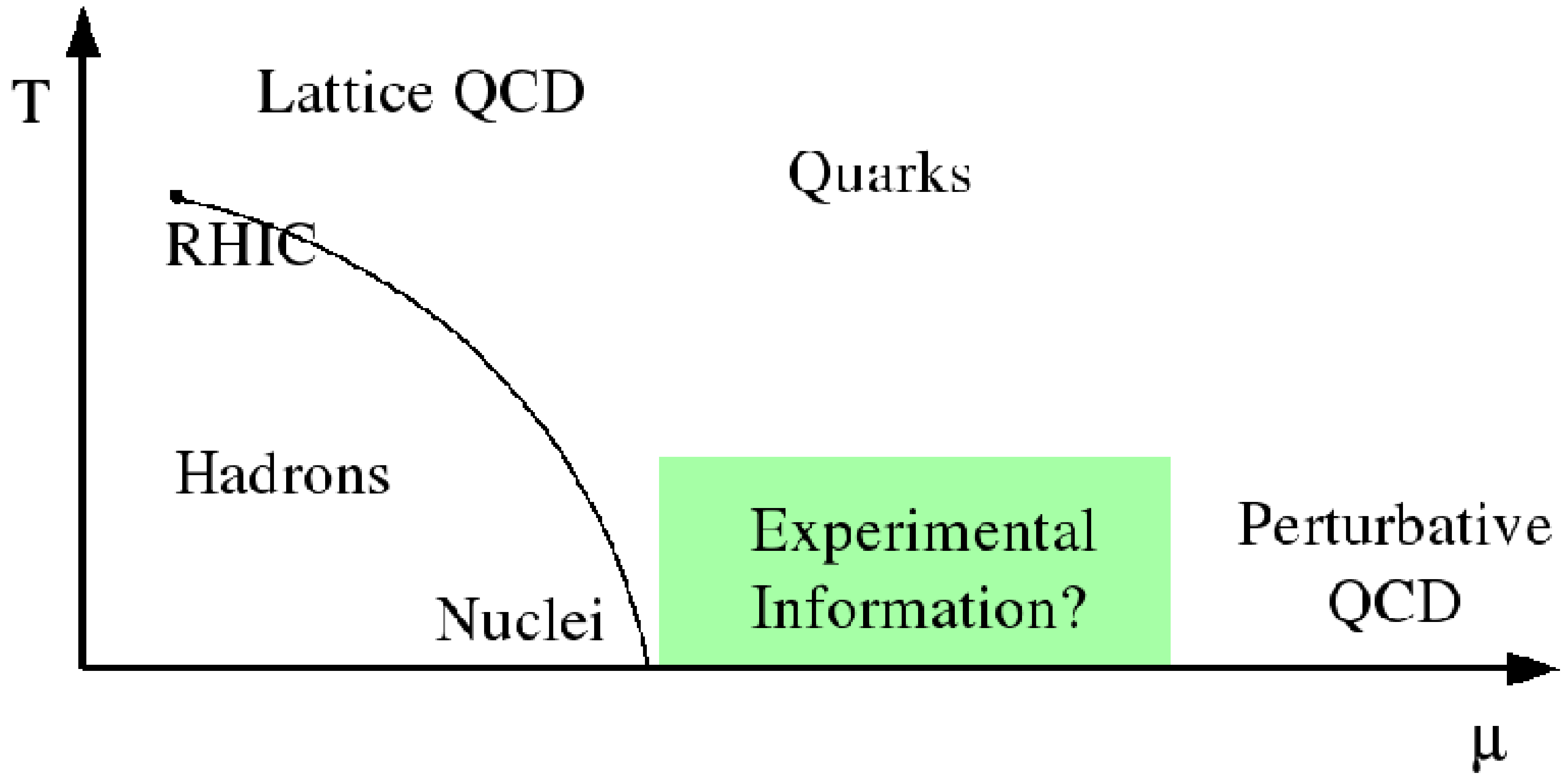


Outline

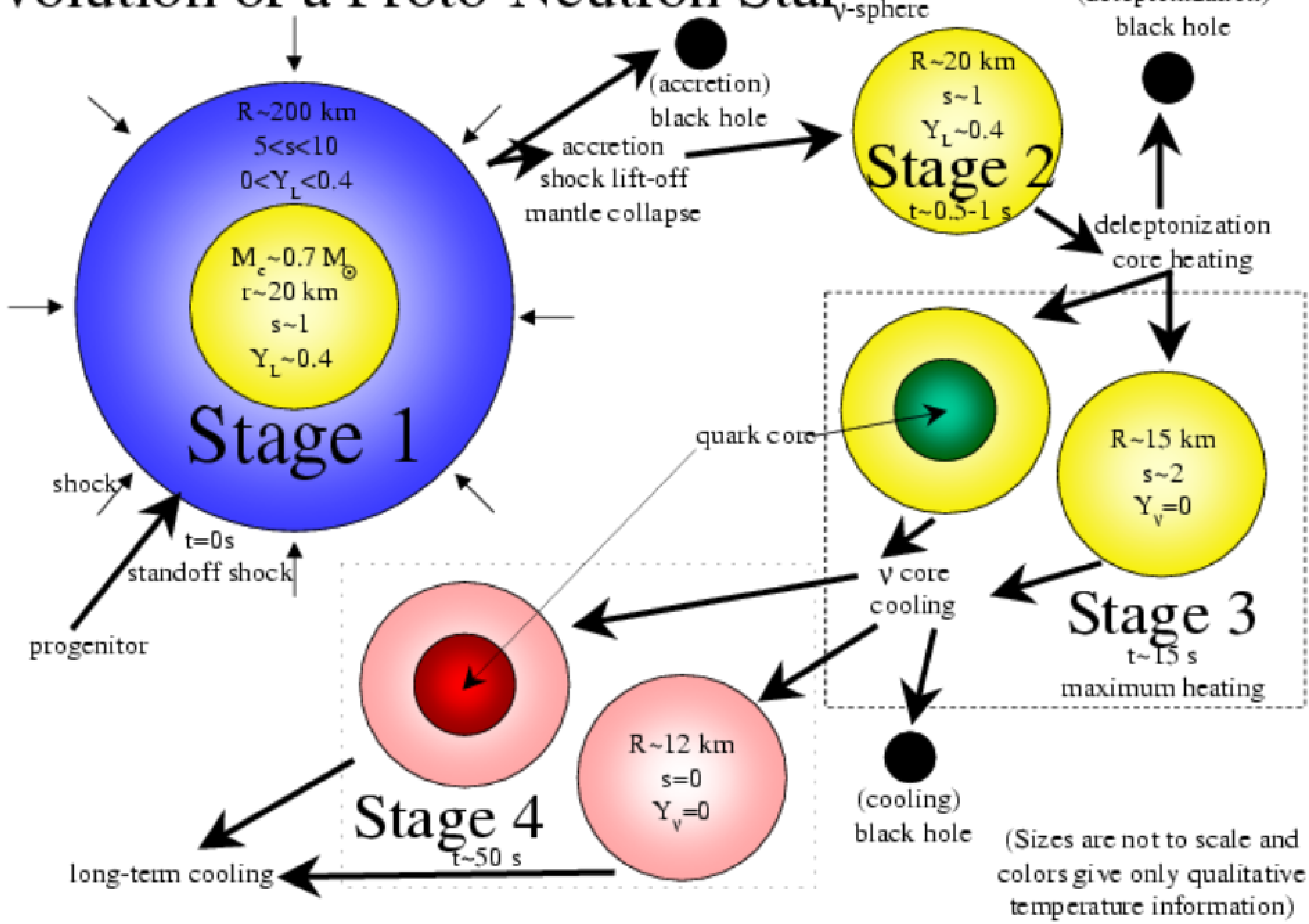
- What? Why? and How? of Quark Matter in Neutron Stars
- Quark Matter and Color Superconductivity
- Bare Strange Quark Stars and their Crusts
- Observations of Quark Matter in Neutron Stars
- Conclusions and Summary

Why study quark matter in neutron stars?

- The ground state of matter at sufficiently large density must consist of deconfined quarks.
  Itoh (1970), Bodmer (1971), Collins & Perry (1975), Baym & Chin (1976), Freedman & McLerran (1978)
- The critical density of the "deconfinement" phase transition is not well known - but could very well be lower than the central density of neutron stars
- The confirmation of the existence of quark matter in neutron stars would provide an observational constraint on QCD and would provide important input for the description of neutron stars

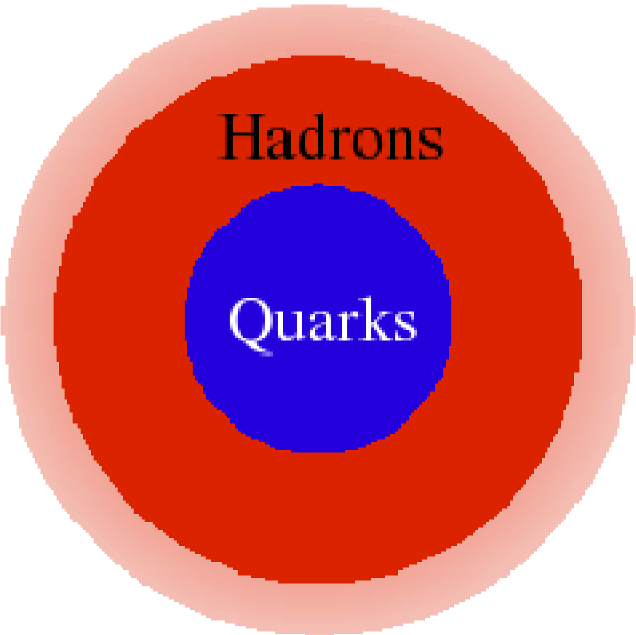


Evolution of a Proto-Neutron Star

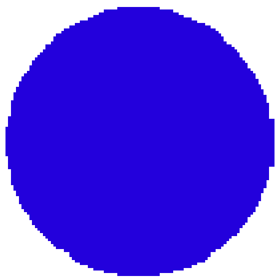


Quark Star Phenomenology

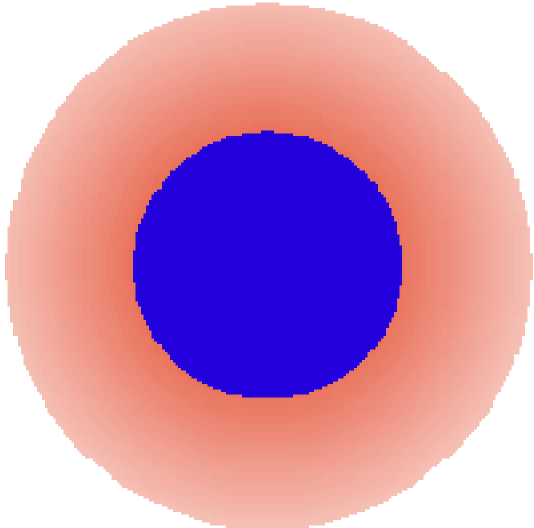
- There are (loosely) four kinds of neutron stars containing quark matter
- Hybrid stars exist only on the assumption that the central density of a neutron star is large enough that quarks become deconfined
- "Bare strange quark stars" require the additional assumption that strange quark matter is absolutely stable (Energy/baryon less than 931 MeV = mass of Fe)
- Strange quark stars may have a crust of hadronic matter. This crust may be separated from the quark core by a large electric field if electrons are present.
- Strange quark stars may have a quark crust



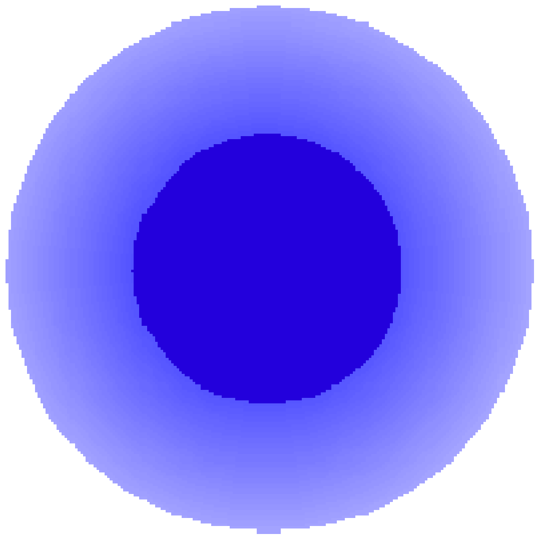
Hybrid Neutron Star (large surface tension)



Bare strange quark star



Bare strange quark star (with crust)



Bare strange quark star (with quark crust)

Color Superconductivity

- A one-component system of fermions with a net attractive interaction has a ground state which is unstable with respect to the formation of Cooper pairs.
- One-gluon exchange is attractive in the 3-bar channel - the ground state is antisymmetric in color, flavor and spin. Furthermore, the ground state has the structure:

  $$\varepsilon^{ijk}\varepsilon^{\alpha\beta k}$$

  This is color-flavor-locking (CFL).

  Bailin and Love (1984), Alford, Rajagopal, and Wilczek (1998), Rapp, et. al (1998)
- Naively, we expect pairing when the Fermi surfaces are close - this is frequently the case and nearly all quark matter in neutron stars contains pairs of some type.
- The strange quark mass may be sufficiently large - The 2SC phase.
- Color-neutrality - homogeneous quark matter should be color-neutral. This implies that the CFL phase is electrically neutral without electrons.

  Alford and Rajagopal (2002), Steiner, Reddy, and Prakash (2002)
- Additional "stresses" on the system may decrease the gap or favor unpaired states

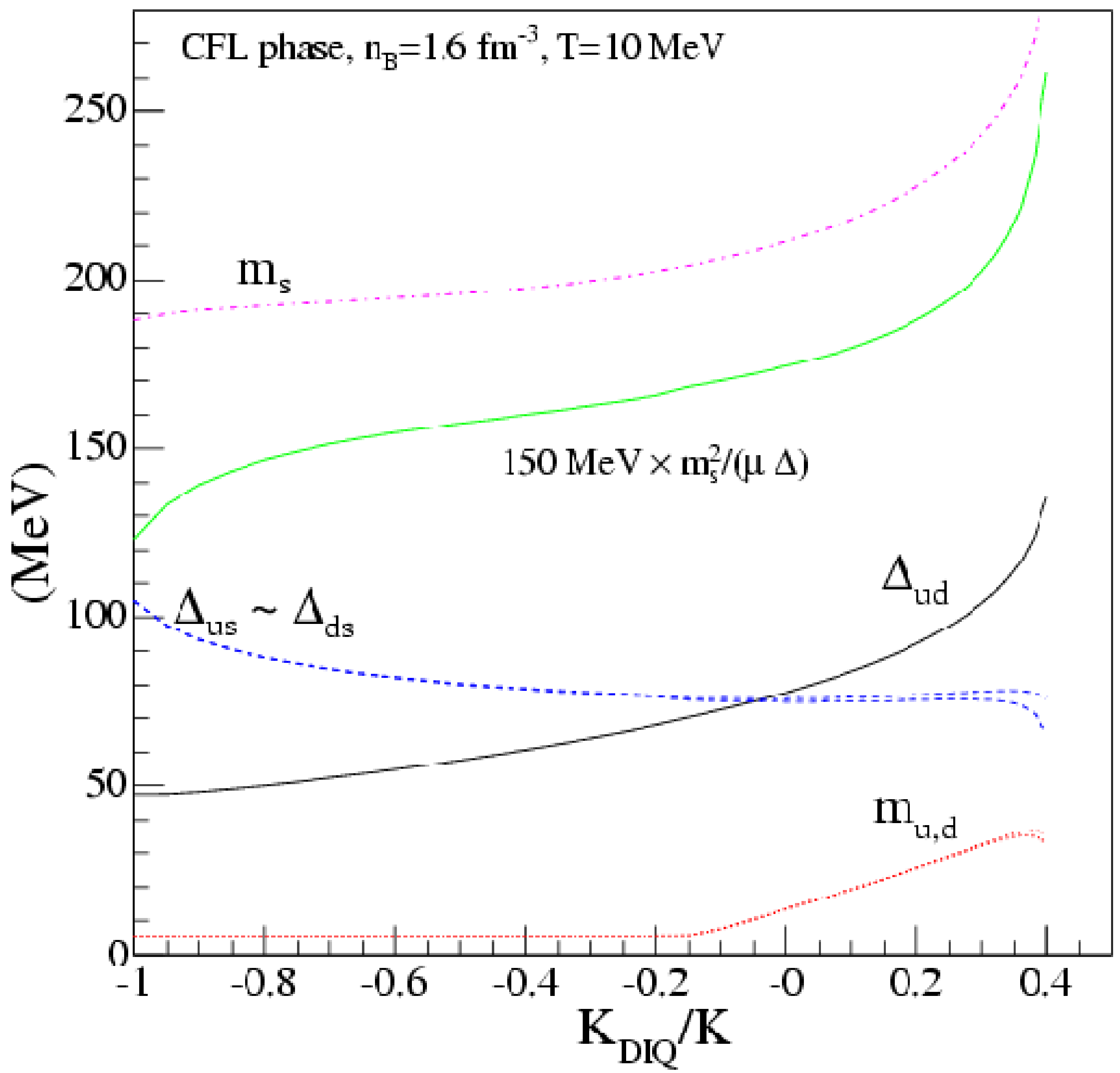
Models of Quark Matter

- Bag model - Free fermions with non-perturbative effects subsumed into a negative pressure, the "bag constant".
- NJL models - The high-energy degrees of freedom (gluons) are integrated out
  Nambu and Jona-Lasinio (1961)
  - Dirac term:
    $\bar{\psi}(i\partial - m)\psi$
  - Quark-anti-quark four-fermion interaction:
    $G(\bar{\psi}\psi)(\bar{\psi}\psi)$ - provides spontaneous breaking of chiral symmetry
  - Quark-quark four-fermion interaction:
    $G_{\mathrm{DIQ}}(\bar{\psi}\psi_c)(\bar{\psi}_c\psi)$ - gives color-superconductivity (CFL, 2SC)
  - Quark-anti-quark six-fermion interaction:
    $\det_f K(\bar{\psi}\psi)(\bar{\psi}\psi)(\bar{\psi}\psi)$ - Breaks axial U(1)

    't Hooft (1986)
- High-Density Effective Theory
  Hong (2000)
  - Simplifies the Dirac structure by removing anti-particles
  - Qualitatively similar results to NJL

Color Superconducting 't Hooft Interaction

- Quark-quark six-fermion interaction: $\det_f K_{\mathrm{DIQ}}(\bar{\psi}\psi_c)(\bar{\psi}_c\psi)(\bar{\psi}\psi)$
  Further modifications to the quark masses and gaps: $\bar{\psi}\Delta^2\psi$, $\bar{\psi}_c\left(\Delta\left\langle\bar{\psi}\psi\right\rangle\right)\psi$
  Rapp et. al. (1998), Schaefer (2002), Steiner (2005)
- Natural flavor-mixing structure from the determinant
- The value of the coefficient of the six-fermion quark-quark interaction can significantly modify the phase structure.
- For K_{DIQ} >0.4, the paired phases break down completely



Steiner (2005)

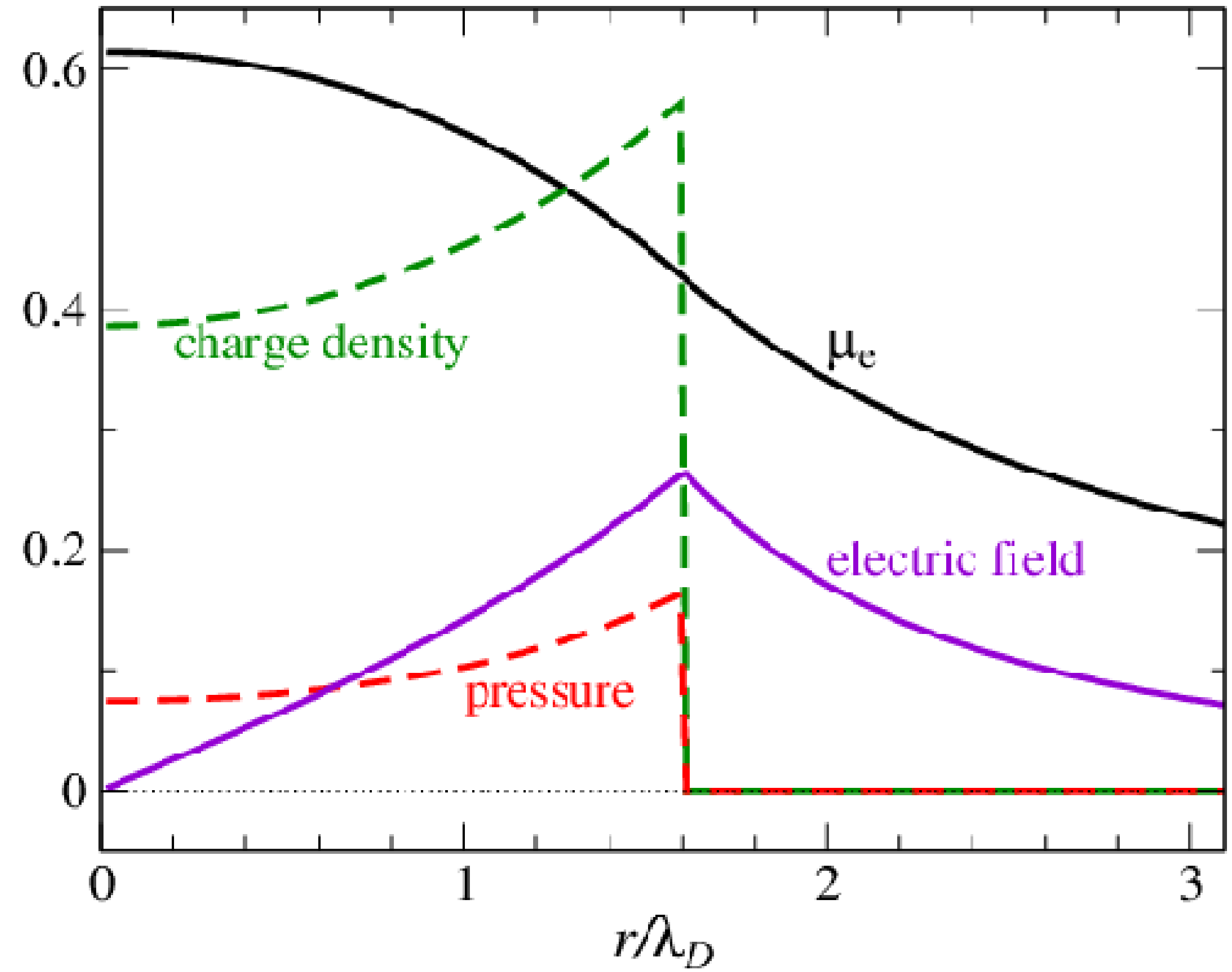
Strange Quark Stars - The Basics

- Bulk strange quark matter can be more stable than ordinary hadronic matter. If you increase the number of degrees of freedom in a system of fermions, you tend to decrease the energy.
  Bodmer (1971), Witten (1984)
- Hypernuclei and hyperon masses imply a small amount of strangeness is unstable.
- Strange quark stars form in Type II supernovae as normal neutron stars, until a small amount of strange quark matter is created. Conversion wave.
- Droplets of strange quark matter, "strangelets", convert neutron stars to strange quark stars.
- Strange quark matter is positively charged, unless it is color-neutral CFL quark matter.
- Old paradigm: Electrosphere surrouding strange quark star creates a large electric field
- Suspend nuclear matter on the surface - a nuclear crust on a strange quark star
- The crust is blown off by super-Eddington photon luminosity created by electron-positron pairs produced by the large electric field

- Strange quarks stars can have strange crusts
  Haensel, Zdunik and Schaeffer (1986), Jaikumar, Reddy, and Steiner (2005)
- Strangelets embedded in a gas of electrons - removes the large electric field

Anatomy of a Strangelet

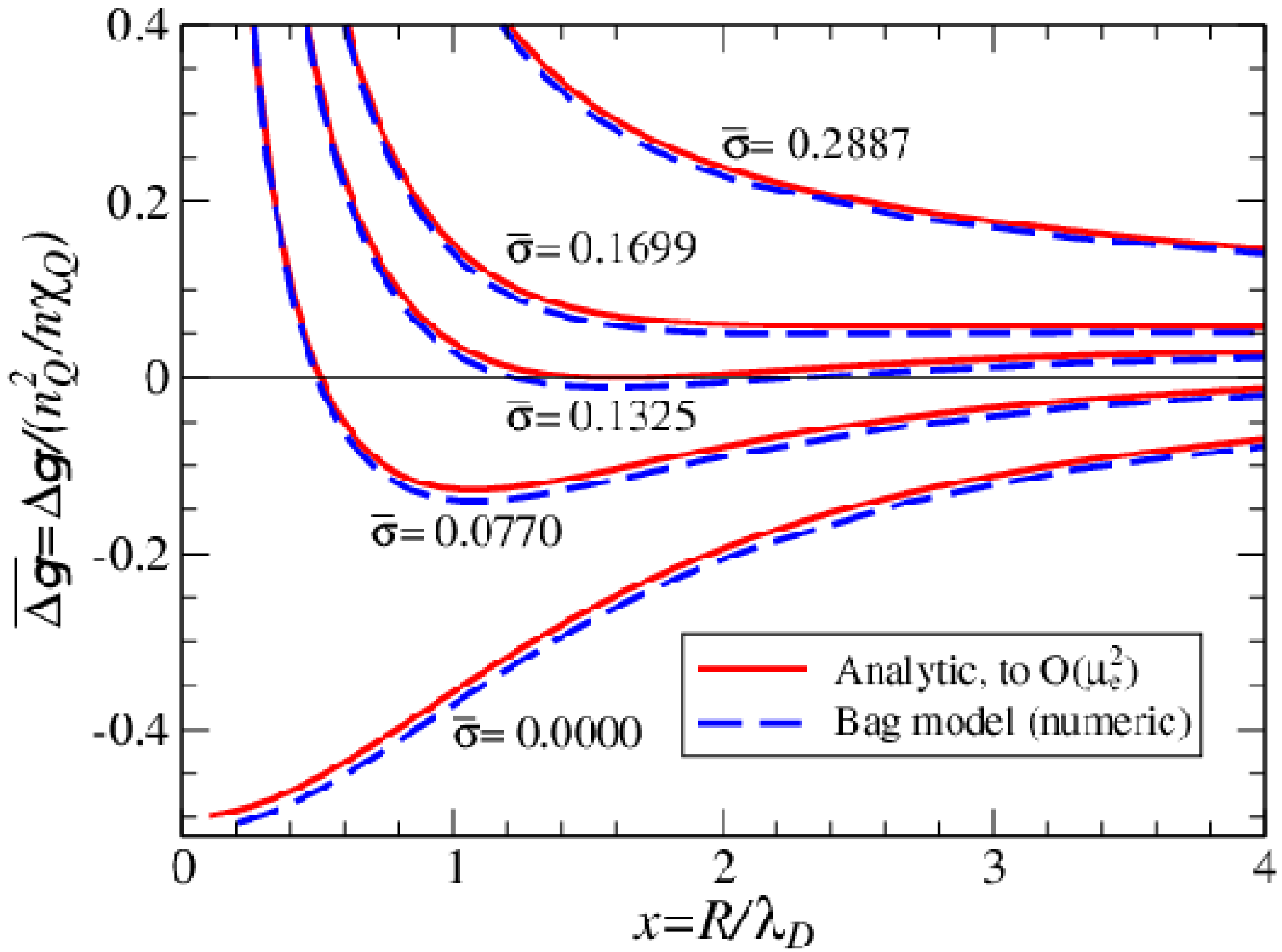
- We assume that strange quark matter is absolutely stable
- Does a crust exist on the surface of a strange quark stars? Are strangelets stable towards fusion?
- Is the gibbs energy per quark of one strangelet at zero pressure and zero temperature less than the gibbs energy per quark of bulk strange quark matter?
- Pressure of matter:
  $P = P_0 + \mu_Q n_Q + \chi_Q \mu_Q^2/2$
- Solve the Poisson equation and treat the quarks in the Thomas-Fermi approximation



Profile of a typical strangelet in the crust
Alford, Rajagopal, Reddy, and Steiner (2006)

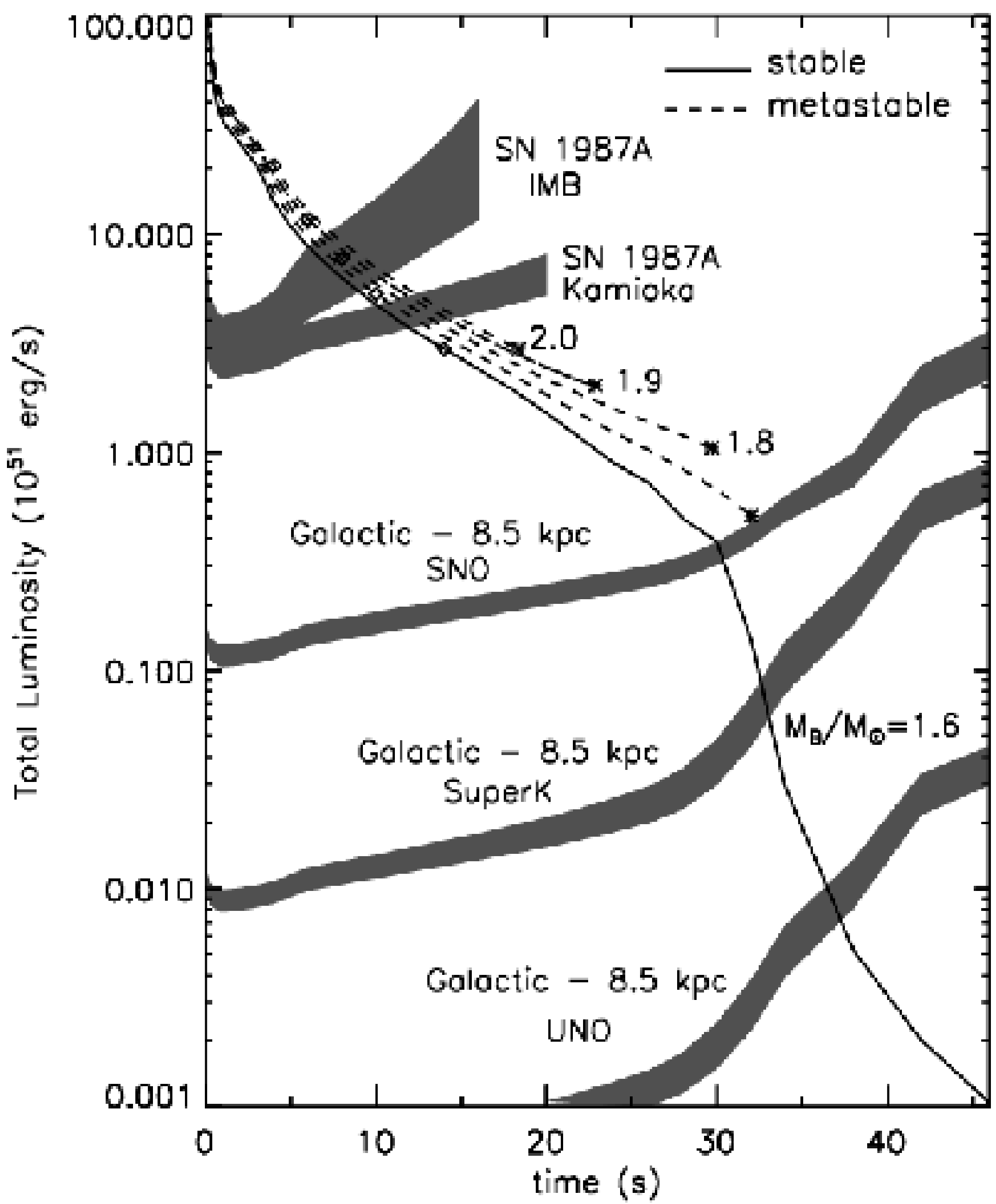
Droplets in the Crust

- Pressure of matter:
  $P = P_0 + \mu_Q n_Q + \chi_Q \mu_Q^2/2$
- Within this (good) approximation, the whole problem can be solved analytically.
- Energy gain of creating droplet:
  $\Delta g = -n_Q^2 f(x)/(4\chi_Q n_0)$
- Energy cost from surface tension
  $\bar{\sigma} = \chi_Q \sigma/(\lambda_D n_Q)$
- The present of a crust depends sensitively on the surface tension of quark matter and the strange quark mass.
- Trivial to interpret results in light of future determinations of n_Q and χ_Q.



Alford, Rajagopal, Reddy, and Steiner (2006)

Observational Signatures - PNS Evolution of a Hybrid Star

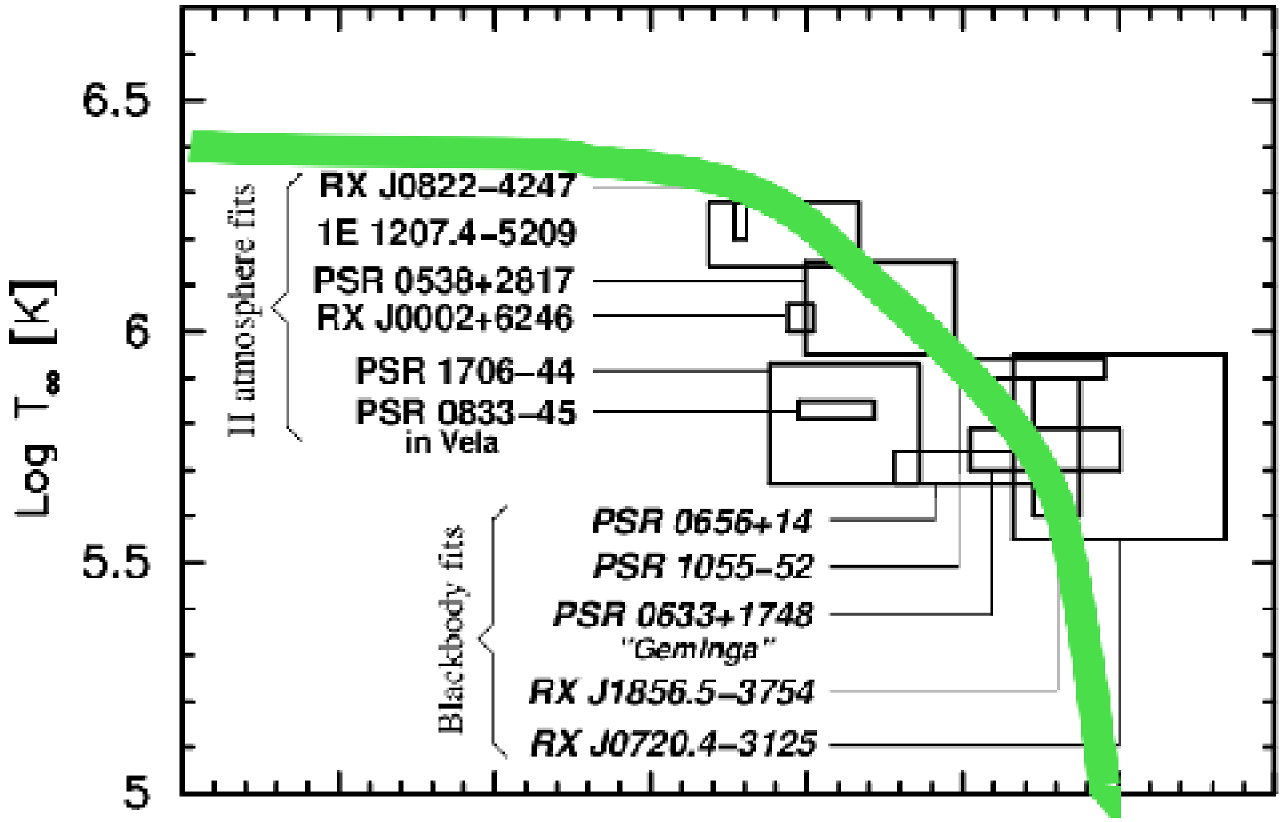


Pons, et. al. (2001)

- The neutrino signal from a galactic supernova will be visible for 30 or more seconds in modern neutrino detectors.
- The neutrino signal may be affected by the presence of quark matter in several ways:
  - Metastability - the neutrino signal disappears
    Pons, et. al. (2001)
  - Superconductivity - the cooling may slow down briefly.
    Carter and Reddy (2001)
  - Goldstone bosons - Neutrino mean free paths comparable to unpaired quark matter
    Reddy, Sadzikowski, and Tachibana (2002)
- There is a lot of recent work on the transport properties of quark matter which may have observable implications
- Strange quark stars would have strange neutrino signals

Observational Signatures - Hybrid Neutron Star Cooling

- Neutron star cooling in hadronic neutron stars - modified or direct URCA
  $n+n \rightarrow n+p+e+\bar{\nu_e}$ vs.
  $n \rightarrow p+e+\bar{\nu_e}$
- Quark matter allows direct URCA ($d \rightarrow u+e+\bar{\nu_e}$), unless it is superconducting - quark matter can lead to enhanced cooling.
  Iwamoto (1980), Carter and Reddy (2000), Page, et. al. (2000)
- CFL matter has a very large thermal conductivity

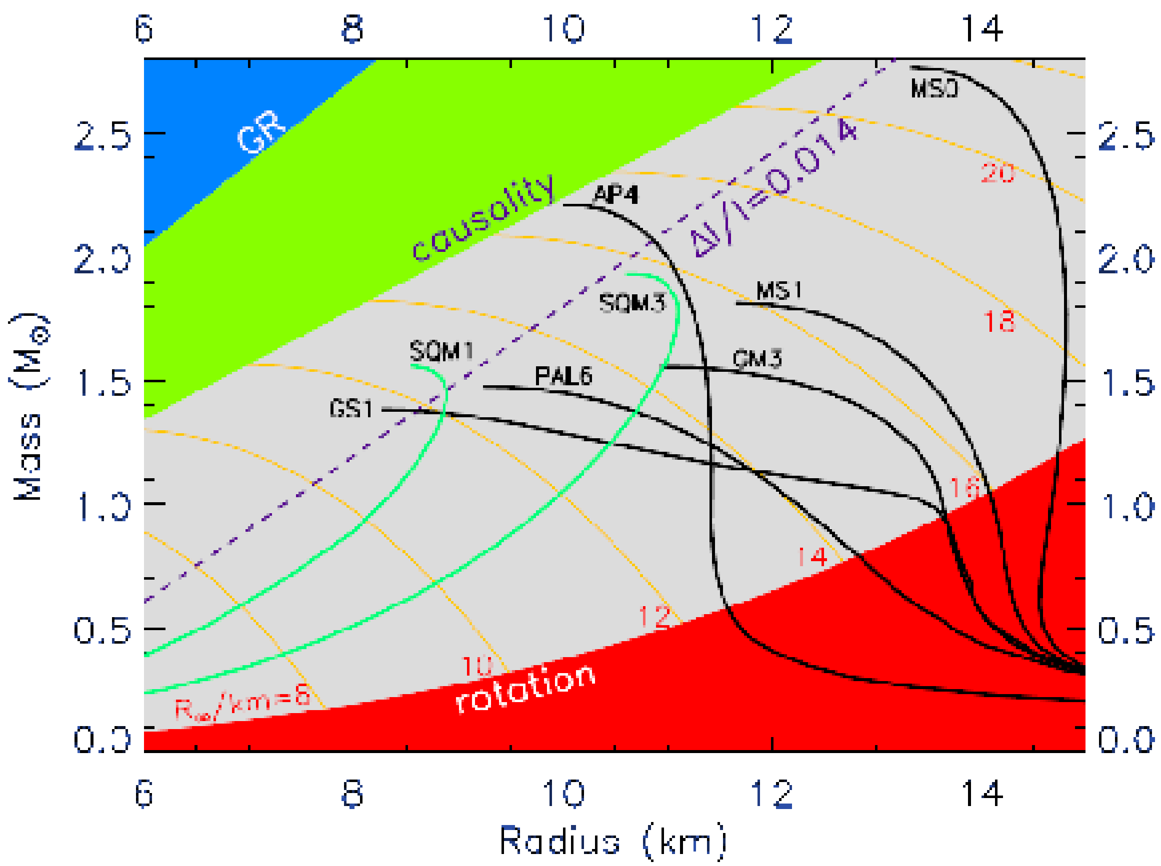


Page, et. al. (2004)

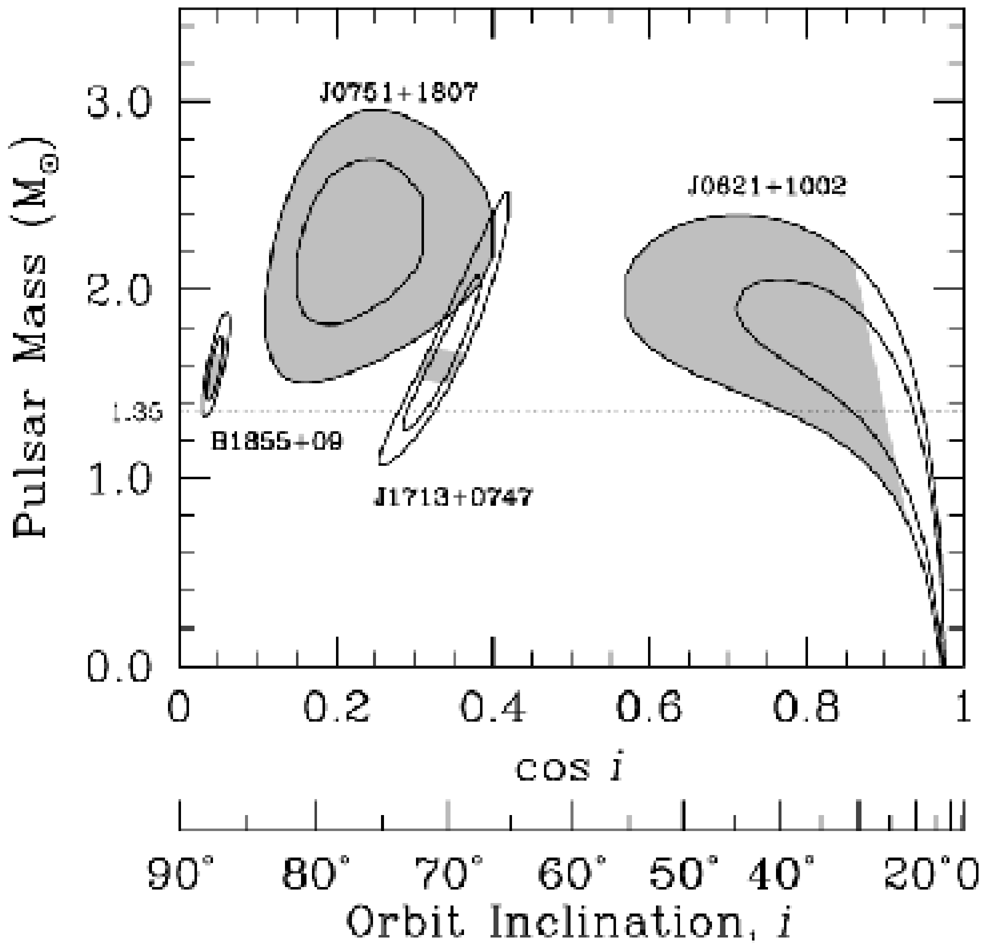
- Present uncertainties are too large to confirm or rule out quark matter
  Yakovlev et. al. (2004)
- Stars that are too cold for their age imply the presence of quark matter.

Observational Signatures - Mass Measurements

- Equations of state which contain quark matter have smaller maximum masses and smaller radii because the equation of state is softer.
- A sufficiently large neutron star mass would also rule quark matter (either in the form of hybrid or strange quark stars)



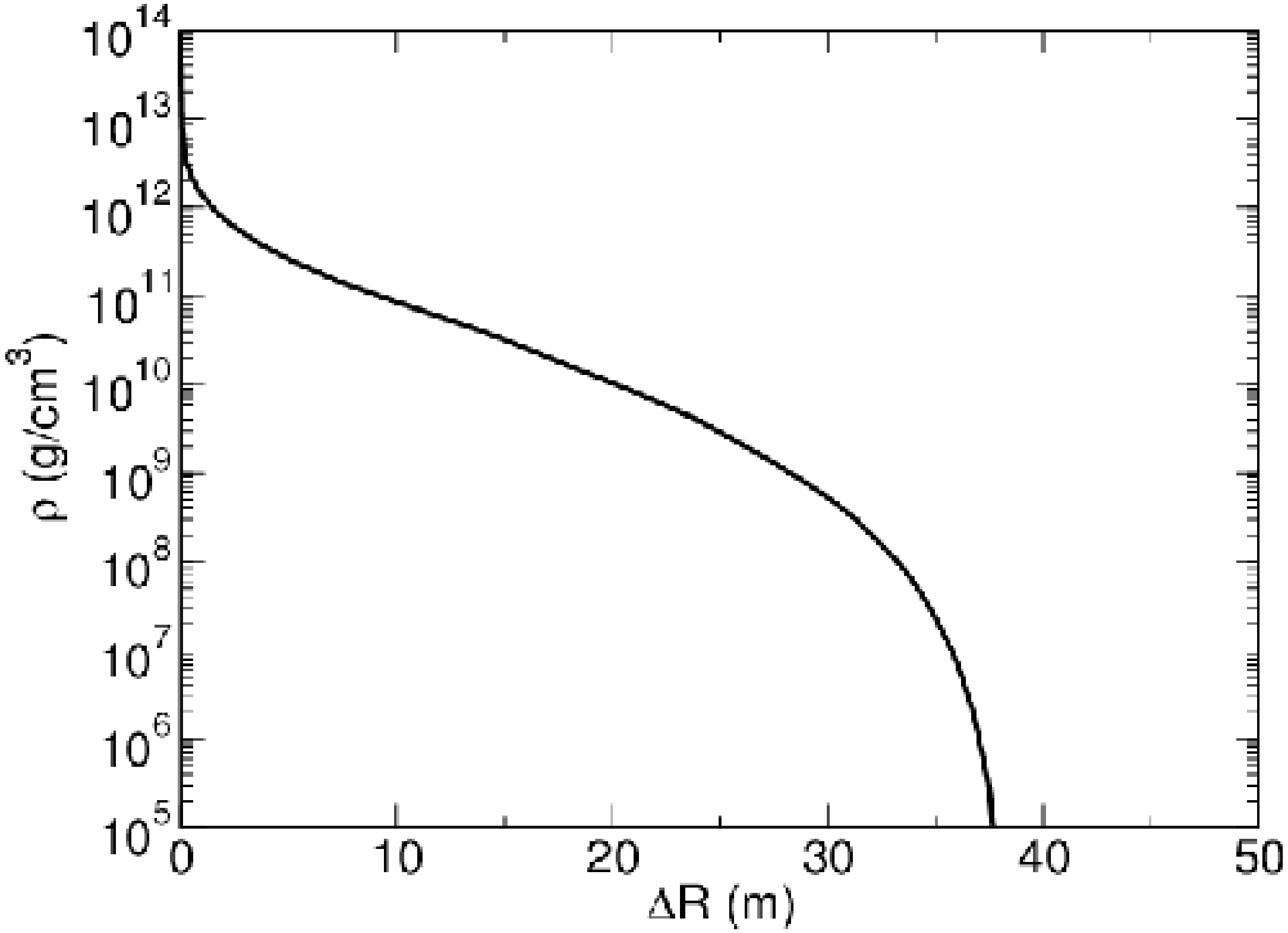
Lattimer and Prakash (2004)



Nice, Splaver, and Stairs (2003)

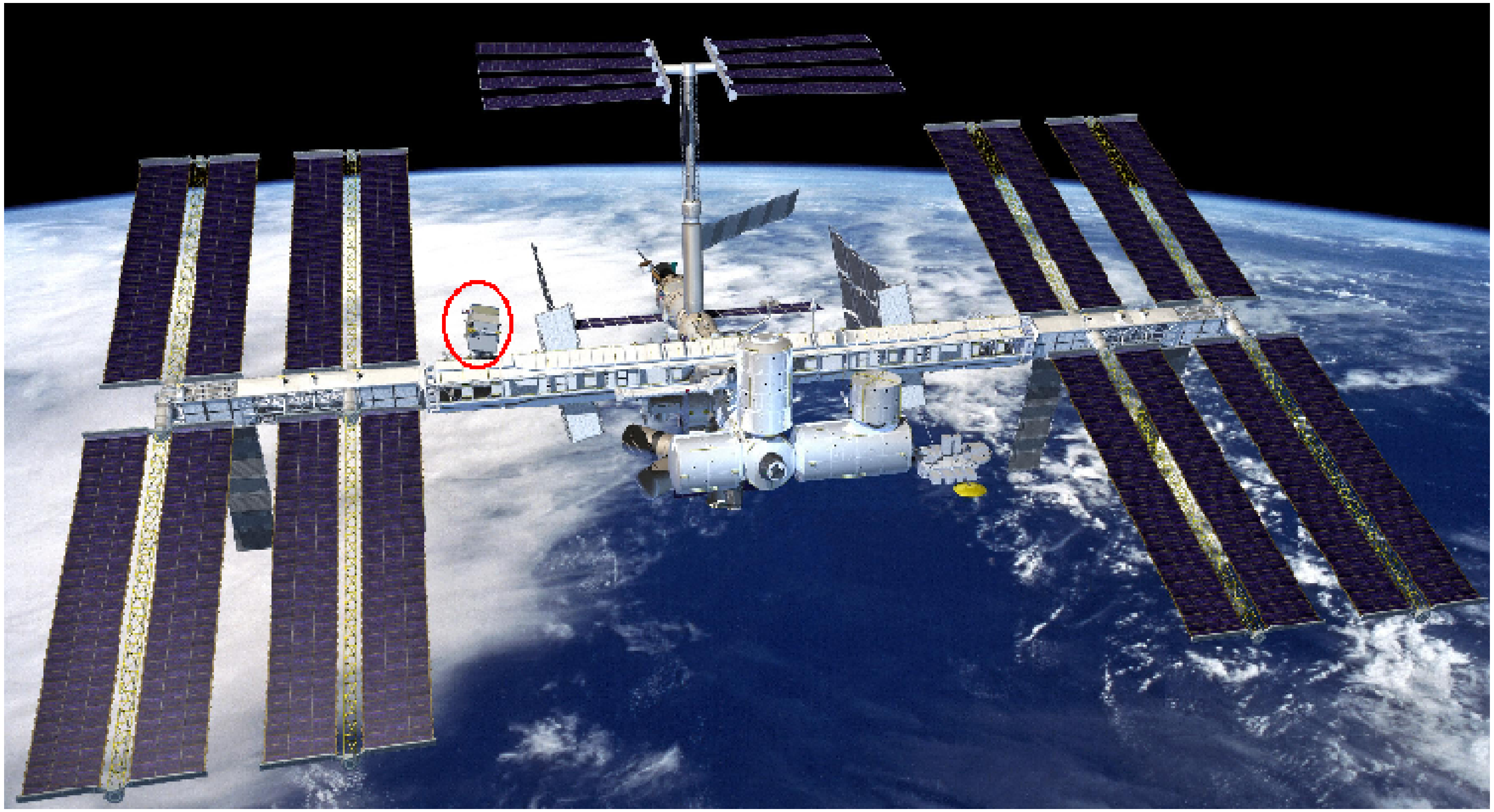
Observations of Neutron Star Crusts

- The crust of a strange quark star is qualitatively different from that of a normal neutron star
- Soft Gamma-ray Repeaters (SGR's) - Neutron stars which undergo "starquakes" which result in gamma-ray flares
- These flares excite crust oscillation modes
- Toroidal modes are sensitive to the thickness of the crust
- X-ray bursts and superbursts also can probe the crustal physics.
- Deep crustal heating mechanism in normal neutron stars is the thermonuclear burning of Carbon
- In strange quark stars, the energy source is the conversion of nucleons to strange quark matter



Jaikumar, Reddy, and Steiner (2005)

Search for Strangelets with AMS



Taken from E. Finch

- Stranglets would be a component of the cosmic ray flux
- If the surface tension of quark matter is sufficiently small, we predict a peak in the observed strangelet distribution.
- Z ~ 70-100, A ~ 600 for a typical set of numbers

Summary

- Neutron stars are an ideal laboratory for QCD in regions of the phase diagram which are otherwise unobservable.
- It is not at all unlikely that we could confirm or rule out the presence of quark matter in neutron stars in the near future.
- The color-superconducting 't Hooft interaction can qualitatively modify the nature of dense matter.
- Strange quark stars may have strange crusts. The existence of a crust would have several observable consequences.